Pilot Interaction With Cockpit Automation: Operational Experiences with the Flight Management System

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ABSTRACT

Because of recent incidents involving glass-cockpit aircraft, there is growing concern with cockpit automation and its potential effects on pilot performance. However, little is known about the nature and causes of problems that arise in pilot-automation interaction. In this paper, we report the results of two studies that provide converging, complementary data on pilots' difficulties with understanding and operating one of the core systems of cockpit automation, the Flight Management System (FMS). A survey asking pilots to describe specific incidents with the FMS and observations of pilots undergoing transition training to a glass cockpit aircraft served as vehicles to gather a corpus on the nature and variety of FMS-related problems. The results of both studies indicate that pilots become proficient in standard FMS operations through ground training and subsequent line experience. But even with considerable line experience, they still have difficulties tracking FMS status and behavior in certain flight contexts, and they show gaps in their understanding of the functional structure of the system. The results suggest that design-related factors such as opaque interfaces contribute to these difficulties which can affect pilots' situation awareness. The results of this research are relevant for both the design of cockpit automation and the development of training curricula specifically tailored to the needs of glass cockpits.

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INTRODUCTION

There is growing concern with the potential effects of increasing levels of cockpit automation on pilots' performance. These effects seem to be related to the fact that automation changes the nature of the pilot's role on the flight deck. Pilots become system managers who are monitoring systems and who intervene only when changes are necessary or unanticipated situations occur (Billings, 1991). Instead of hand-flying the airplane, pilots act indirectly through instructions to the automation in order to control the aircraft. This may remove the pilot from the loop decreasing system awareness, especially if feedback on automation status and behavior is limited.

Despite the growing interest in pilot-automation interaction, only limited empirical data are available about the nature of problems that occur with the current generation of automated cockpit systems. Pilot reports to the Aviation Safety Reporting System

(ASRS) have been analyzed but these data are limited to a subset of incidents that were severe enough to threaten safety (e.g. Eldredge et al., 1991). Some analyses of selected incidents have been conducted (e.g. Norman, 1990) in the context of larger theoretical treatments of human-automation interaction. Questionnaire techniques have been used to obtain ratings about glass cockpit pilots' attitudes and opinions concerning current cockpit automation (e.g. Wiener, 1989; Lyall, personal communication[1]; James et al., 1991; "Automation Comment", 1991[2]). While these rating data provide interesting suggestions, they do not reveal the dynamics of pilot-automation interaction or specific areas of difficulty. Also, these pilot opinion data would be more informative if they were complemented by observational data.

We utilized two complementary approaches to obtain data about pilot-interaction with one of the core systems of cockpit automation, the Flight Management System (FMS). In one study, we asked pilots to describe in detail problems or incidents that they had

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[1] Beth Lyall, America West Airlines, 1991.
[2] Automation comment. (1991, February). Feedback, No.23 pp. 2-5.

experienced with the FMS, especially ones where FMS behavior surprised them. The corpus of incidents generated by this self-report technique was analyzed to identify the nature of pilot difficulties and the flight contexts in which they occurred.

In a second study, we observed crews transitioning to a glass cockpit aircraft during a number of line-oriented simulation (LOS) on a fixed-base simulator. Pilot-FMS interaction and crew-instructor communications during and after the simulated scenarios were analyzed to identify difficulties in pilot-FMS interaction. The two studies are complementary because they use different "corpus gathering" techniques, and because they sample both experienced glass cockpit pilots and experienced pilots in transition to a glass cockpit aircraft.

The results of this research add to a better understanding of the effects of flight deck automation on pilot performance. This data may be helpful in the design of future flight decks by pointing at-specific sources of difficulty such as poor feedback on automated system status and behavior. The results can also be used to refine and expand training programs for glass cockpit aircraft. They provide information on specific FMS modes, functions, and flight situations where pilot-FMS interaction is most troublesome.

INTRODUCTION TO THE FLIGHT MANAGEMENT SYSTEM

The following section provides a brief, simplified overview of the Flight Management System (FMS). The FMS supports pilots in a variety of tasks such as flight planning, navigation, performance management, and flight progress monitoring. One of its major functions, and the function of primary interest in the context of the reported studies, is automatic flight path control.

The major FMS controls in the cockpit are the Mode Control Panel (MCP) and the multifunction keyboards of two Control Display Units (one for each pilot). FMS-related cockpit displays are the CDU multifunction display, two Attitude Director Indicators

(ADI), and two Horizontal Situation Indicators (HSI). Figure 1 illustrates the typical location of these different FMS components within a generalized glass cockpit.

The Control Display Unit (CDU) consist of a multifunction control unit (keyboard) and data display. The keyboard is used by pilots to enter data that define a flight path and to access flight-related data available on various pages within the CDU page architecture. The pilot-entered flight path, continuously updated to reflect the current flight status, is presented on the map display of the Horizontal Situation Indicator (HSI). This allows pilots to monitor progress along the path. In the HSI Plan Mode, the pilot can visually check modifications to the active flight plan.

The Mode Control Panel is used to activate different automatic flight modes (e.g. VNAV, LNAV, HDG SEL, LVL CHG). The pilot can also use knobs on the MCP to dial in targets for individual flight parameters (airspeed, heading, altitude, and vertical speed) which are tracked by the system if a corresponding automatic flight mode is activated. To find out which FMS modes are currently active, the pilot can monitor the Flight Mode Annunciations on the Attitude Director Indicator (ADI). These provide data on the active (or armed) pitch and roll modes and on the status of the autopilot(s). They also in indicate the status and mode of the autothrottles which can be set to manual or automatic mode for speed and altitude control. The various FMS interfaces and autoflight functions provide the pilot with a high degree of flexibility in terms of

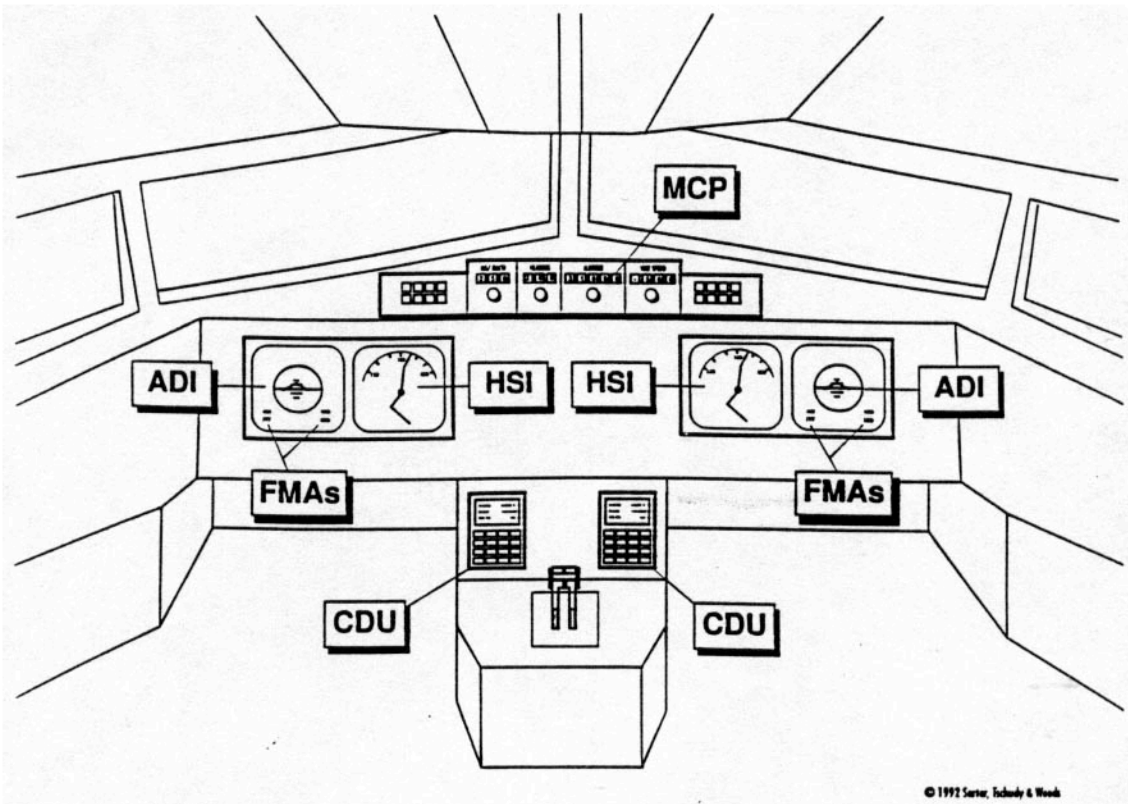

Figure 1: Flight deck controls and displays related to pilot-FMS interaction within a generalized glass cockpit.

selecting and combining levels of automation to respond to different situations and requirements.

It is important to remember that there are various modes of automatic flight control that range between the extremes of automatic and manual. The highest level of automatic control occurs in the VNAV (Vertical Navigation) and LNAV (Lateral Navigation) mode. In these modes of control, the pilots enter (or, in their words, "program") a sequence of targets that define an intended flight path into the CDU, and then activate the automatics by selecting VNAV (Vertical Navigation) and/or LNAV (Lateral Navigation) through controls on the Mode Control Panel (MCP). The Flight Management Computer (FMC) automatically controls the aircraft to follow the desired flight path. At this strategic level of automation, the FMS pursues a sequence of target values without the need for further intervention by the pilot. This is particularly helpful in situations that allow for long-term planning with a low likelihood of deviations from the plan (e.g. cruise phase of flight).

When the pilot needs to quickly intervene and change flight parameters (e.g. in terminal areas), other lower levels of automation are available. The pilot can enter target values for different flight path parameters (i.e. airspeed, heading, altitude, vertical speed) on the Mode Control Panel (MCP). He then activates one of the corresponding modes (e.g. Heading Select or Level Change), and the target will be captured and maintained automatically until target or mode of control are actively changed by the pilot.

An important characteristic of automatic flight path control is the high degree of dynamism. Transitions between modes of control occur in response to pilot input and to changes in flight status. Automatic mode changes can occur automatically when a target value is reached (e.g. when leveling off at a target altitude) or based on protection limits (i.e. to prevent or correct pilot input that puts the aircraft into an unsafe configuration).

Both the flexibility of the FMS and the dynamism of flight path control impose cognitive demands on the pilot. He has to decide which level and mode of automatic control to use in a given set of circumstances, and he also has to track the status and behavior of the automation. This latter task requires that he attends to and integrates data from a variety of indications in the cockpit such as the Flight Mode Annunciations on the Attitude Director Indicator, the visualization of the programmed route of flight on the Horizontal Situation Indicator, or the display of target values on the Mode Control Panel.

RESEARCH ACTIVITIES

Study 1: Pilot Reports of FMS-Related Surprises

Background and Methods

The pilot report corpus was generated through a questionnaire, distributed to experienced airline pilots flying the B-737-300. This survey expands on results from a portion of a study by Wiener (1989) who asked B-757 pilots to rate statements concerning their attitude towards cockpit automation. Two of the statements were specifically related to FMS operations (see Figure 2).

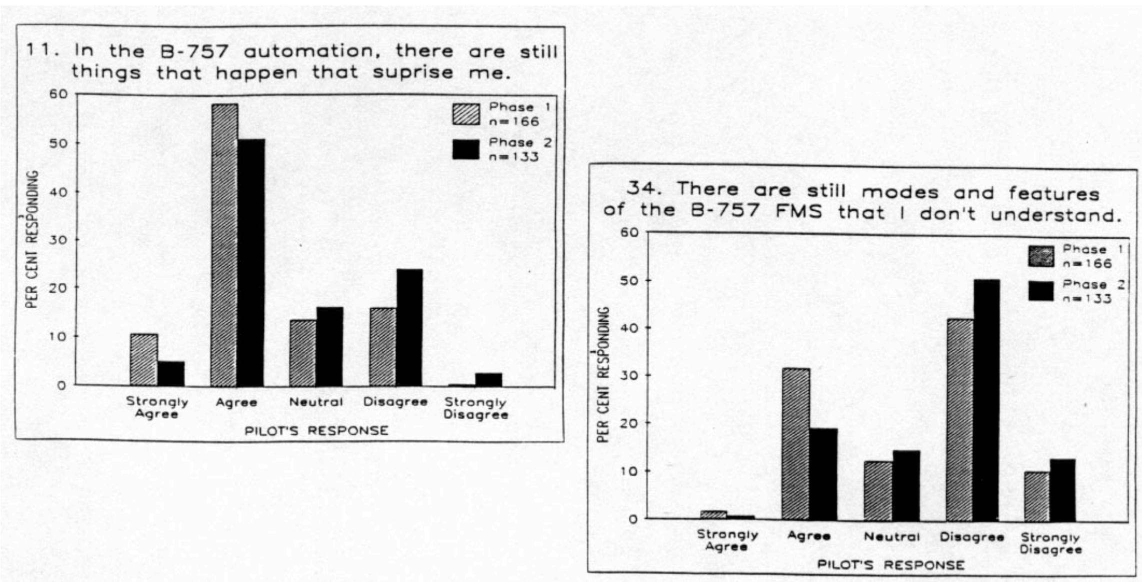

Figure 2. Results of a pilot survey concerning "glass cockpit"-related issues (adopted from Wiener, 1989, p. 28 and 58). (Phase 1 = data collected in 1986; Phase 2 - data collected in 1987; volunteer 757 pilots served as subjects).

Interestingly, the responses show that a rather large number of pilots with more than one year of experience on the B-757 agree that they are still being surprised by the automation (- 55% of the pilots) or that they do not understand all of the FMS modes and features (- 20% of the pilots). Given the implications and potential consequences of these rating data, it seems important to examine in detail what are the nature and circumstances of these surprises and gaps in pilots' mental models. We followed up Wiener's results by asking B-737-300 pilots to rate their agreement/disagreement with the above two statements on a five point scale (strongly agree, agree, neutral, disagree, strongly disagree). But more critically, we asked them to describe in detail as many instances as possible of surprises they had actually experienced and modes they did not understand. The survey vehicle thus served as a "corpus gathering" technique, that is, a means for "the identification and description of naturally occurring phenomena" (Reason, 1990). In other words, it captured some of the variety of real-world difficulties and recurrent patterns of pilot-automation interaction.

Results

Table 1 summarizes the background data on the pilots who responded to the survey. The survey was distributed to 887 B-737-300 line pilots from one airline company; responses were received from 135 pilots.

Table 1: Background and flight experience of pilots responding to the survey.

Age (n=134):	42.6 (8.5) y/o	[mean (std. dev.)]		
Flight Time on the B-737-300 (n=132):	944 (613) hrs	[mean (std. dev.)]		
Seat on the B-737-300 (n=134):	Captain	75 pilots		
	F/O	59 pilots		
Total Flying Time (n=134):	7714 (4978) hrs	[mean (std. dev.)]		
Previous Commercial Jet Aircraft Flown (n=124):				
	B 727	38	B 757/767	18
	B 737-200	19	B 747-400	1
	DC - 8	16		
	B 747	2	DC - 10	29
	DC - 9	1		

The pilots' ratings of the two statements on cockpit automation basically replicate Wiener's (1989) results.

Table 2. Percentages of pilots' responses to the first statement: “In the 737-300 automation, there are still things that happen that surprise me."

<table>
<tr><th>RATING</th><th>ALL PILOTS (N=135)</th><th>< 1,200 HRS OF LINE EXPERIENCE (N=97)</th><th>>/= 1,200 HRS OF LINE EXPERIENCE (N=37)</th><th>NO PREVIOUS GLASS COCKPIT EXPERIENCE (N=104)</th><th>PREVIOUS GLASS COCKPIT EXPERIENCE (N=19)</th></tr>
<tr><td>STRONGLY AGREE</td><td>18</td><td>22</td><td>5</td><td rowspan="2">72</td><td rowspan="2">42</td></tr>
<tr><td>AGREE</td><td>49</td><td>57</td><td>33</td></tr>
<tr><td>NEUTRAL</td><td>7</td><td>5</td><td>11</td><td>7</td><td>5</td></tr>
<tr><td>DISAGREE</td><td>22</td><td>14</td><td>43</td><td rowspan="2">21</td><td rowspan="2">53</td></tr>
<tr><td>STRONGLY DISAGREE</td><td>4</td><td>2</td><td>8</td></tr>
</table>

Table 3. Percentages of pilots' responses to the second statement: “There are still modes and features of the B-737-300 FMS that I don't understand."

<table>
<tr><th>RATING</th><th>ALL PILOTS (N=135)</th><th>< 1,200 HRS OF LINE EXPERIENCE (N=97)</th><th>>/= 1,200 HRS OF LINE EXPERIENCE (N=37)</th><th>NO PREVIOUS GLASS COCKPIT EXPERIENCE (N=104)</th><th>PREVIOUS GLASS COCKPIT EXPERIENCE (N=19)</th></tr>
<tr><td>STRONGLY AGREE</td><td>12</td><td>15</td><td>0</td><td rowspan="2">54</td><td rowspan="2">11</td></tr>
<tr><td>AGREE</td><td>33</td><td>36</td><td>25</td></tr>
<tr><td>NEUTRAL</td><td>16</td><td>21</td><td>8</td><td>13</td><td>21</td></tr>
<tr><td>DISAGREE</td><td>25</td><td>20</td><td>39</td><td rowspan="2">33</td><td rowspan="2">68</td></tr>
<tr><td>STRONGLY DISAGREE</td><td>14</td><td>8</td><td>28</td></tr>
</table>

More important for the purpose of developing countermeasures to any existing problems related to pilot-automation interaction are pilots' descriptions of specific instances of FMS surprises and modes/features that they had difficulties with.

Corpus of Pilot-Reported-ted FMS Surprises and Problematic FMS Modes/Features

Pilots were asked to describe instances where FMS behavior surprised them and to indicate modes/features of FMS operation that they did not understand. There were no sharp boundaries between the incidents elicited by the two questions. Pilot reports are categorized according to their underlying theme. The major categories refer to a) Vertical Navigation (VNAV) modes, b) data entry, c) uncommanded mode transitions, d) infrequently used modes and features of the FMS, e) surprising flight director commands, f) monitoring of active target values, g) the availability of multiple methods for achieving a goal, h) the lack of data propagation within the control display unit (CDU), and i) the effects of partial system failures. For each category in the corpus we provide a short description of the kinds of problems reported, the number of pilot reports on problems in this category, and, for some categories, an abbreviated example. Surprises or unclear features of the FMS that were only reported by one pilot are not included in the corpus.

A) VNAV-related problems

The largest number of reported problems refer to Vertical Navigation Modes (VNAV). These are suWivided into the four categories '1INAV logic and calculations", "Switching between VNAV and MCP descent modes", the 'VNAV Speed Descent mode in general", and the "Disengagement of the APPROACH mode".

VNAV logic and calculations 38 Reports

Pilots indicate that the algorithms underlying the calculation of a VNAV path are not transparent to them. They can not visualize the intended path, and therefore they are sometimes unable to anticipate or understand VNAV activities initiated to maintain target parameters (25 reports). VNAV control actions are often described as being surprisingly abrupt (4 reports). Several pilots report that they have been surprised by VNAV when it failed to start the descent upon reaching the top-of-descent point (TOD) (9 reports).

Abbreviated example:

VNAV was used for a path descent. Although the displayed TOD was reached, and autothrottles (A/Ts), autopilot (A/P) and VNAV were engaged, the aircraft did not start to go down. The pilots finally figured out that this happened because they had not changed their initial cruise altitude entry in the CDU after ATC told them to level off at FL 290 instead of the originally planned FL 310. Meanwhile, the TOD point had been passed. The airspeed had rolled back from 280 kts to 190 kts. When the descent was initiated by the pilots, the FMC (Flight Management Computer) used an excessive rate of descent (6,000 fpm) to get down to the path. This caused an ATC alert, and the actual airspeed increased to the maximum limit speed.

Switching between VNAV and MCP descent modes 11 Reports

These examples refer to situations where pilots had a descent properly programmed and both VNAV (Vertical Navigation mode) and LNAV (Lateral Navigation mode) engaged when ATC asked them for an unanticipated level-off or change in heading. They report uncertainty as to whether or not the reengagement of VNAV after compliance with the clearance by means of MCP interventions would bring them "back on track". They have problems with keeping track of active target values related to different FMS subsystems under such circumstances.

VNAV Speed Descent Mode in general 8 Reports

Pilots indicate that they do not understand how the VNAV Speed Descent works in terms of its targets, protections, and its operational logic.

Disengagement of the Approach (APPR) mode 6 reports

Some pilots report that they were not able to disengage the APPR mode when required to do so. This problem is especially important as it occurs at a fairly low altitude, under time pressure and sometimes in congested traffic areas.

Example:

During the final descent, the pilots were unable to deselect the APPR mode after localizer and glideslope capture when ATC suddenly requested that the aircraft maintain the current altitude and initiate a 90 degree left turn for spacing. They tried to select ALT HOLD (Altitude Hold mode) and HDG SEL (Heading Select mode) on the MCP to disengage the APPR mode and comply with the clearance but neither mode would engage and replace the APPR mode. They finally turned all autoflight systems off.

Data Entry 54 reports

There was a large number of reports related to the rejection of attempted input into the CDU due to different software versions running on the FMS. While the survey was underway, three slightly different FMS software versions were in use. According to the reports, this resulted most frequently in unsuccessful attempts to enter a new crossing restriction during the approach because the required data entry format and procedure is not the same for the three software versions. Pilots also commented that the 'invalid Entry" message they received in these cases did not help them find the correct input format. These data entry problems frequently occurred when the pilots were working under time pressure, and in some cases they contributed to altitude violations.

C) Uncommanded Mode Transitions 28 reports

Pilots report that they are surprised by "uncommanded" mode transitions which occur upon reaching a target state or for protection purposes. Most often, the reports refer to the automatic reversion from Vertical Speed mode (V/S) to Level Change mode (LVL CHG) which occurs if the airspeed deviates from the target range due to an excessive rate of climb or descent. One potential consequence of this automatic mode transition is that the vertical rate changes dramatically without any intervention by the crew. Pilots' reports seem to indicate that such uncommanded changes are difficult to track given current cockpit displays and indications.

D) Infrequently used features/modes 14 reports

Pilots report that they do not understand modes and features of the FMS that they rarely use (e.g. the Required Time of Arrival (RTA) feature). However, they also comment that they do not think of these as critically important features.

E) Flight Director (FD) Bars 11 reports

Pilots describe cases where the FD bars commanded pitch attitudes which seemed to be inadequate or unnecessarily abrupt. Some pilots report that, as a result, they loose confidence in the FD bars.

F) Active Target Values 10 reports

In some situations, it seems to be difficult for pilots to keep track of what are the currently active target values. The pilot reports indicate that one of the major sources of this problem is the interaction between the values selected on the MCP and those selected within the CDU. Pilots also commented that, while the MCP targets can immediately be seen on the MCP, the FMS targets are sometimes "hidden" in the CDU page architecture.

Example:

As a protective measure, VNAV climbs and descents are constrained by the selected MCP altitude. For example, in order for a preprogrammed FMC descent to begin upon reaching the TOD point, a lower than CRZ altitude has to be selected on the MCP. If pilots forget to do so, the aircraft will maintain cruise altitude beyond the TOD and the airspeed will slow down. Some pilots report mat they have been surprised by this aircraft behavior because they did not realize that in this case the MCP target overrides the CDU target.

G) Multiple Methods 10 reports

Some pilots mention that, for certain tasks, there seems to be an overwhelming number of possible methods to do the job. Their reports indicate that there is a cognitive load associated with learning and deciding on which method to use for a particular task in a particular flight context. The reports point to the tradeoff between providing pilots with flexibility and imposing additional cognitive load on them.

H) Lack of data propagation 9 reports

Pilots report that they are sometimes surprised by the effects of interactions between target values entered on different but interrelated CDU pages. They suggest that certain data should propagate automatically to functionally interrelated CDU pages.

Example:

A frequently described example is the case where, during the cruise phase of flight, the airspeed entry on the CRZ page of the CDU is changed but the new data do not propagate to the DES page. If the new cruise speed is lower than the originally programmed descent speed pilots are surprised upon reaching the TOD point, when the aircraft starts to accelerate rather than decelerate.

I) The effects of partial system failures 3 reports

These pilots report that they are unsure of the consequences of partial FMS failures. After such failures, they can not tell which subsystems are still active, which subsystems are available, or how the failure may interact with the active flight control mode. These reports implicate potential problems with both pilots' mental model of the FMS structure and with the indications of FMS status and behavior.

The corpus of reported difficulties in pilot-FMS interaction was generated through one technique that sampled a small part of the relevant user population. In order to converge on a more comprehensive and meaningful assessment of existing difficulties in pilot-automation interaction we conducted a complementary study where we observed crews in transition to highly automated aircraft during a number of simulated flight scenarios.

Study 2: Observation of Crews in Transition Training

Background and Methods

To complement the data gathered through pilot reports, we also observed the behavior of experienced pilots who were in the process of transitioning to the B-737-300 aircraft. This transition training involves classroom, computer-based training (CBT), LOS (line-oriented simulation) sessions on a fixed-base trainer, and LOFT (line-oriented flight training) sessions on full-mission simulators. At the end of training, pilots take a 4-hr simulator check-ride in which they have to demonstrate that they are proficient in the following autoflight systems operations: Active Data Base check, FMS and Performance Initialization, Flight Plan Entry, Direct To/Intercept Leg To, Holding Pattern, Installing an Approach, closing a Route Discontinuity, and MCP (Mode Control Panel) Speed Interventions.

We observed 10 pilot crews during fifteen LOS sessions with 6 different scenarios during their transition training on a fixed-base B-737-300 trainer (see Table 4 for a breakdown of crews by scenario).

Table 4. Observed training sessions on the FMS part task trainer.

LOS (Line-Oriented Simulation) Scenario	No. of Observations	Crew
LOS 2	1	A
LOS 3	2	B C
LOS 4	3	D E F
LOS 5	1	F
LOS 6	4	F G H I
LOS 7	4	B D E

Crews A, C, G, H, I, and K were observed only during one of the seven LOS sessions. The other four crews were observed more than once. For example, crew B was observed early in their training (session 3) and again during their last LOS session. The advantage of multiple observations is that the progress of these crews could be examined.

The transition training is carried out using a fixed-base simulator which allows for all flight operations except hand-flying the aircraft below 1,000 ft AGL. It is equipped with all relevant cockpit instruments and displays including a Flight Management System with its associated electronic flight displays and control interfaces described earlier (Figure 1).

Each of the observed LOS sessions requires 3 hours to complete. As in line operations, one of the pilots is assigned the role of pilot-flying, the other carries out the tasks of the pilot-not-flying. From time to time, the simulation is interrupted by the instructor to ask questions or to discuss the flight situation with the pilots.

The simulation scenarios consist of a complete flight, including cockpit setup, takeoff and landing, and they are designed to cover predefined sets of objectives emphasizing FMS operations. Abnormal and increasingly difficult simulations such as system failures are introduced at the later stages of training.

Throughout each LOS session, an observer was present (the first author) who was knowledgeable about both the scenarios and the FMS procedures and activities required to handle each scenario.

The observer collected two types of data. First, she encoded crew-FMS interactions - the methods used to carry out given tasks and errors or difficulties that occurred. A second source of data was the discussion between the instructor and the crew which occurred

during the scenario and after the scenario was completed. These instructor-crew communications help to reveal gaps in FMS-related knowledge and misconceptions in the pilots' model of the system. For example, the discussions indicated whether the pilots were capable of explaining their interaction with the FMS, or whether they simply used "recipes" to operate the system without fully understanding how their input lead to the desired outcome.

The LOS scenarios on the fixed-based simulation facility provide a meaningful window on pilot-automation interaction. They allow for the collection of verbal reports as frequent and extended interruptions naturally occur to answer pilots' questions and to comment on their performance (Woods, 1992). Such interventions are not desirable in the context of real-time full-mission simulation training.

Results

Table 5 contains the flight background of the ten crews. Note that 6 of the 10 observed crews were "mixed crews" in the sense that one of the pilots had previous "glass-cockpit' experience while the other one came from a "non glass-cockpit."

Table 5. Previous aircraft flown by pilots observed during transition training.

Crew	Captain	First Officer
A	B 767	B 727
B	B 767	B 767
C	DC - 10	B 727
D	B 767	DC - 8
E	B 767	B 727
F	B 767	B 727
G	B 767	B 727
H	B 767	B 727
I	DC - 8	B 727
K	DC - 10	DC -8

The observations indicated that pilots can become proficient in basic FMS operations in a fairly short amount of time. Difficulties with these basics were observed only, with very few exceptions, during the first three training sessions (LOS 2, 3, 4). The few difficulties observed concerned basics such as entering data in the correct format, finding relevant data in the CDU pages, or carrying out tasks such as FMS Initialization. During these first 3 sessions, it was, in some cases, difficult for pilots to keep track of who is in charge and what are the currently active target values. Difficulties arose in managing the Horizontal Situation Indicator (HSI), i.e., selecting ranges and modes of presentation.

During the last three training sessions (LOS 5, 6, 7), pilot errors and questions focused on gaps in their understanding of the underlying functional structure of the FMS. Table 6 provides an overview of the most frequently encountered problems and questions.

Table 6. Most frequently observed problems during transition training to the B-737-300.

- **Availability/Disengagement of Modes**

  For example: Knowledge of LNAV capture criteria or ways to disengage the APPR mode

- **Keeping track of Uncommanded ModeTransitions**

  For example: Awareness of automatic transition to ALT HOLD mode upon level-off, and subsequent requirement to re-engage a Climb-Mode for changing altitude

- **VNAV Targets and Logic**

  For example: Visualization of FMS-calculated vertical profile

- **Multiple Methods**

  For example: Pilots often indicated that they were not sure whether there were other ways of achieving a goal or how to choose among multiple methods

Frequently, pilots were able to describe FMS behavior during standard operations. For example, a pilot could describe the states and activities of the autothrottles (A/Ts) during takeoff and climb. But the same pilot would have difficulties applying this knowledge to a specific and more complicated operational situation, e.g. an aborted takeoff. This is often referred to as the problem of inert knowledge (Glaser, 1984).

In summary, the physical appearance and the "recipes" for carrying out standard tasks could be learned in a fairly short amount of time. However, even during the last training sessions, many of the observed pilots show gaps in their understanding of the overall functional structure of the system as indicated by their problems in dealing with complex or novel tasks and situations. The above problems were most often seen with pilots who transitioned from a "non-glass cockpit" aircraft. While their "glass-experienced" colleagues "only" had to get used to minor differences between their previous aircraft and the B-737-300, these pilots had to learn a whole new cockpit concept.

As a result, it appears from our observations that there are disadvantages to "mixed" training crews, i.e. crews where only one of the two pilots has previous glass-cockpit experience. This pilot who could focus on deeper issues about how to manage the automation capabilities in diverse contexts often was forced to wait while the other crew member explored more basic concepts and flight situations. In turn, the pilot with no previous experience on a highly automated aircraft sometimes did not ask all of his questions because he felt that he was slowing down the training process.

Overall, we observed the same kinds of difficulties during the late stages of transition training as were reported by line pilots in the survey study. The two studies used complementary data collection techniques (pilot reports and behavioral data through observation of training simulations) and sampled different levels of experience with glass cockpit aircraft. The combined results create a corpus of specific flight situations and FMS behaviors where difficulties arise in pilot-automation interaction. At this level, the results may be useful to system designers interested in incremental improvements of the current system and its pilot interfaces. Similarly, the results may be useful to those responsible for training pilots to work with current cockpit automation by highlighting particular modes of the FMS and particular flight situations where pilots have difficulty tracking and anticipating FMS behavior. However, one may also interpret the specific reported and observed difficulties in a larger perspective—what do these results tell us about the factors that are important for effective human-automation cooperation?

DISCUSSION

Breakdowns in Pilot-Automation Interaction

The corpus of reported and observed difficulties provides a picture of the kinds of complexities that can arise in pilot-automation interaction and the kinds of task contexts where these complexities can affect performance. Knowledge of these mechanisms is essential to be able to better design the interface between pilots and automation from the point of view of a cooperative human-machine cognitive system (Woods, 1986; Hutchins, 1991). This knowledge also indicates how training programs may need to change in fundamental ways to accommodate the changes in the human's role in highly automated aircraft.

The corpus of reported and observed difficulties indicates that pilots can lose situation awareness (Sarter and Woods, 1991) with respect to FMS status and behavior. Wiener (1989) has summarized his results on cockpit automation in the phrase, "the three most commonly asked questions in glass cockpits are: 'What is it doing?' 'Why did it do that?' 'What will it do next?"' The corpus reveals specific pilot-FMS interaction difficulties that can be grouped under these three questions. For example, difficulties in tracking active target values and FMS behavior in some modes can contribute to losing track of "what the automation is doing". Uncommanded mode transitions can create situations where the crew can be surprised—"why did it do that?" One common factor contributing to such an incomplete or faulty assessment of system status and behavior seems to be weak feedback from the FMS displays and interfaces (Norman, 1990). Another common factor implicated in many of the problems noted in the corpus is incomplete or buggy mental models of how various modes of the FMS work and especially how they interact with each other in different flight contexts. If the pilot has difficulty monitoring and understanding automatic system behavior, it will also be difficult for him to project or anticipate future states—"what will it do next".

The problem of weak feedback on system status and behavior is a common deficiency in human-computer interfaces (Norman, 1990). While all of the necessary data on FMS status may be available somewhere in the cockpit displays and the CDU page architecture (see Figure 1), finding, integrating and interpreting all of the relevant data to build an assessment of current and future FMS behavior can be a demanding cognitive task, especially given the time demands of actual flight operations (Woods, 1991). Many examples of inadequate feedback occurred in the corpus including difficulties integrating data on FMS status distributed over different cockpit displays or CDU pages, difficulties anticipating uncommanded mode changes, difficulties assessing the implications of changes to the instructions given to the FMS (e.g., en route changes in cruise speed may interact with pre-programmed values for the descent phase on a different CDU page), difficulties visualizing the descent profile programmed in VNAV. Weak feedback can increase cognitive workload in several ways: by increasing demands on pilots to remember information and by increasing the need to rely on mental models of FMS structure and function to assess or project FMS behavior.

Another factor that seemed to contribute to difficulties noted in the corpus is incomplete or buggy mental models of how various modes of the FMS work and how they interact with each other in different flight contexts. The various FMS interfaces and autoflight functions provide the pilot with a high degree of flexibility in terms of selecting and combining levels of automation to respond to different situations and requirements. However, this flexibility creates new sources of cognitive workload for the pilot. One issue is simply that there are a large variety of ways that the automation can be used and that having a detailed and complete understanding of how these various automation modes work in detail is a demanding new knowledge requirement for the glass cockpit pilot. The corpus results indicate that there are infrequently used modes (e.g., VNAV speed descent is rarely used in US airspace) that pilots do not understand completely. Second, the flexibility of the automation requires that pilots understand how different modes interact and the consequences of transitions between modes in various flight contexts. Third, the pilot needs to develop knowledge and strategies for how to use the flexibility of the automation in different flight circumstances. The corpus results indicate that pilots tend to adopt and stick with a small repertoire of strategies because their knowledge about the advantages and disadvantages of the various options for different flight contexts is incomplete.

Both the-self-reports and the training observations indicate that pilots do not perceive the FMS as one large integrated system consisting of a variety of closely related, interacting subsystems such as the MCP or the CDU. They rather tend to refer to the MCP as a separate system to which they "escape" in case things become too complex or time pressure is too high while working with the CDU. From an engineering perspective, the FMS works in an integrated way. But this property is not sufficiently emphasized in training, and it is not dearly represented in the image the system presents to the pilot through the various displays of FMS status. Our data show that pilots think of and operationally use the MCP and CDU as, at least, two different systems.

Discussion of issues on pilot-automation interaction often focus on the transition from automated to manual control of the aircraft. Our data show that the problematic issue is in fact different. It is important to remember that there are various modes of automatic flight control that range between the extremes of automatic and manual. The FMS provides the pilot with the opportunity to select among and combine a wide variety of modes which results in different levels of automation. The process of gradually moving up and down between these levels of automation is where difficulties in managing the system occur frequently due to problems with keeping track of the states and target values of the various modes. This problem is aggravated by the fact that these transitions are most likely to occur during busy climb and descent phases of flight.

New technology that creates or exacerbates bottlenecks during busy, high tempo, high criticality, event-driven operations, while its benefits tend to occur during routine, low workload situations has been termed "clumsy automation" (Wiener, 1988;1989). Clumsy automation or the clumsy use of technology is a form of poor coordination between the human and the machine. The concept is based on the fact that in complex systems human activity ebbs and flows, with periods of lower activity and more self paced tasks interspersed with high tempo, externally paced operations where task performance is more critical (Rochlin, et al., 1987. An important design feature for well integrated cooperative work between the automation and the human is how the automation supports high workload periods or more difficult tasks. As a result, the effects of factors such as weak system feedback and incomplete mental models of the functional structure of the FMS may only be visible during more difficult or unusual situations (Roth et al., 1987).

The corpus of reported and observed difficulties show that, while pilots can make the FMS work (e.g., by using familiar modes or by switching to less automated modes), they are not always capable of explaining why their input resulted in the desired outcome. In addition, they do not fully exploit the range of capabilities of the system. In case of unusual or novel situations, it may be essential, however, to have a thorough understanding of the functional structure of the FMS and to be able to use this knowledge in an operationally effective way.

While some of this knowledge about how to manage the FMS capabilities is acquired during training, initial operating experience, and line operations, our data from experienced pilots show that there may not be enough time to explore all system options or to figure out the reasons underlying surprises or unclear modes. Furthermore, since the pilots can work around areas in which their knowledge may be buggy or which occur infrequently, incentives for deepening their understanding of the FMS may diminish with time. People are not always accurate in their judgments about how much they know (the degree of calibration) and can overestimate how much they know (an overconfidence bias), especially when the device in question has an opaque interface that provides weak feedback about actual status and behavior.

The concept of clumsy automation reminds us that cognitive work in the automated cockpit is inherently cooperative - between the human crew members and between the pilots and the automation (Woods, 1986; Hutchins, 1991). Therefore, the fact that pilots tend to adopt a limited repertoire of strategies for using the capabilities of the automation creates a potential coordination problem. When two pilots with different preferences have to coordinate their activities and crosscheck inputs without fully understanding the strategies preferred or used by their colleague, they may have problems to maintain situation awareness. Cooperation and coordination is also necessary between the crew and the automation. Thus, for glass cockpit aircraft, cockpit resource management training should be concerned with pilot-automation as well as pilot-pilot coordination and communication.

An additional factor complicating pilot-automation cooperation is the difficult problem of software configuration control. One can assume that software is not a static entity but changes and evolves throughout the life of the system. Our results show that there are operational consequences and design implications which should be taken into account in managing software changes and that version control problems can be a source of difficulties for the crew.

Implications for Design and Training

The corpus of reported and observed difficulties in pilot-automation interaction suggests approaches to improving coordination and cooperation in current and future systems. First, better feedback on FMS status and behavior can support pilots in maintaining situation awareness in high tempo, high workload or unusual flight contexts. One part of this may be to explore new concepts that help pilots integrate diverse data into a coherent, operationally relevant picture of FMS status and behavior, including past behavior, current activities and setup, and future implications (e.g., Woods, 1991). In addition, the pilot-FMS interfaces can be modified to support data access and interface management tasks. Second, training programs and design efforts can address new ways to support pilots in forming and refining their mental model of the functional structure of the FMS.

The current training programs for pilots in transition to glass cockpits can provide pilots with the basic knowledge required to "make the FMS work", especially in standard situations. However, the data in the corpus show that this training may not be sufficient to prepare pilots for dealing with all operationally significant FMS procedures and information for coping with non-standard situations. It may prove important to revise our conception of training experienced pilots for transition to glass cockpit aircraft where the initial training is one part of a longer, continuing learning process with respect to how cockpit automation functions and how it can be utilized as a resource in a wide range of operational circumstances. Training opportunities for pilots flying glass cockpits in line operations may need to be expanded to establish ongoing progressive training through additional information about FMS features that are used less frequently or that can not be tried out in line operations for safety reasons, through opportunities to test and to extend their skills in managing the automation especially in more difficult or unusual flight contexts, and through opportunities to follow up and learn from surprises that they or their fellow pilots have experienced.

The FMS training that we observed emphasized a bottom-up approach oriented towards proficiency in specific tasks by providing "recipes" for system operation. The result that most of the difficulties in the corpus involved non-standard situations and complex interactions of FMS subsystems seems to suggest that a top-down approach would be desirable as an addition or complement. If pilots were provided with an overall mental representation of the functional structure of the FMS, they would be better able to manage and utilize the automated systems in unusual or novel situations. Given that their role has shifted towards the detection of deviations from the expected and towards troubleshooting and managing such situations, this capability seems to be very important for pilots in highly automated aircraft.

In summary, the corpus of observed and reported difficulties in pilot-automation interaction suggests the need for the following improvements in the design and training of the FMS to help pilots exploit the full range of capabilities provided by flight deck automation:

- system states and transitions, goals, and options need to be clearly and coherently indicated to the pilot;

- the user needs to be supported in forming an accurate mental model of the device functionality which is critical for coping with more difficult and unusual flight situations;

- the display and interaction capabilities that mediate pilot-FMS communication need to be tailored to high demand situations and circumstances.

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